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A review on retrofit fuel injection technology for small carburetted motorcycle engines towards lower fuel consumption and cleaner exhaust emission

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ABSTRACT

Most motorcycles in developing countries use carburettors as the fuel delivery system especially for models with cubic capacity of less than 350 cc. However, small gasoline carburetted engines suffer from low operating efficiency, high fuel consumption and produce high level of hazardous emissions. A retrofit fuel injection system (FIS) is a system that is developed to totally replace the conventional carburettor system to improve its fuel economy and exhaust emissions, providing a low-cost alternative in an effort to reduce fuel costs and air pollution. This paper provides a comprehensive review on the retrofit fuel injection technology developed for small gasoline spark ignition (SI) motorcycle engines from 50 cc to 350 cc. Three main retrofit FIS schemes – the throttle body injection (TBI), port fuel injection (PFI) and direct injection (DI) – are compared, in terms of configurations, complexity, costs and performances.

Contents

1. Introduction

Motorcycles equipped with carburettor systems have become the main option of transportation in many countries around the world since the early 1910s. Interests in motorcycles have been the highest in Asia with an estimated 313 million motorcycles on road since 2012. Fig. 1 shows the distribution of worldwide motorcycles in 2012, with Asia accounted for 78% of the total number, followed by Europe (14%) and Latin America (5%). In Asia, China has the highest number of motorcycles (100 million units), followed by India (40 million units) and Indonesia (30 million units) [1]. The continuous growth in the usage of small, carburetted-engine motorcycles especially in developing countries such as India, China, and Vietnam is as a result of up-and-coming economies, enlarged urbanization, improvement of infrastructure and personal wealth [2]. The continuous increase in fuel prices has also

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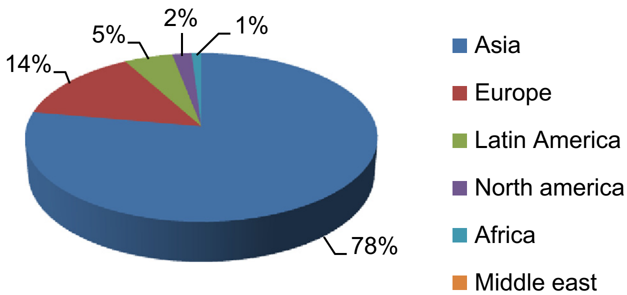

Fig. 1. Worldwide motorcycle fleet.

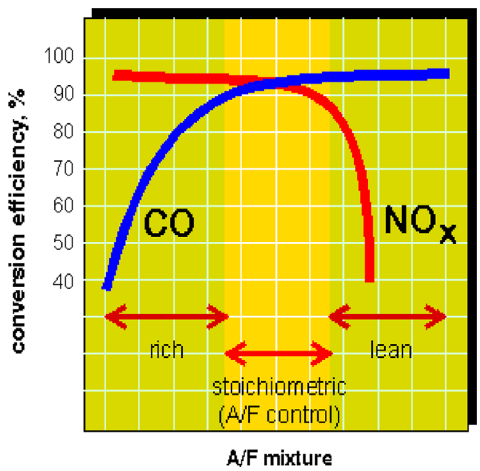

Fig. 2. Efficiency of catalytic converter as a function of A/F.

forced more people to choose motorcycles as a mode of transport due to its smaller engine capacity, hence, lower fuel consumption [3]. However, most of these motorcycles are using carburettor as the fuel delivery system, which is well known for its low operating efficiency, high fuel consumption and high level of hazardous emissions.

It has long been proven that for maximum efficiency and minimum harmful emission production, the correct amount of fuel and air mixture is needed to create a complete combustion in the engine, where the mass of air should be 14.7 times the mass of fuel [4]. This ideal mixture of fuel and air is known as the 'stoichiometric' mixture. However, in practice, this mixture has never been formed perfectly by any machine. Fig. 2 shows the efficiency of the catalytic converter in reducing pollutants as a function of air to fuel ratio (A/F). The use of carburettor cannot closely follow this required ratio because the rate of air and fuel going into the engine cannot be controlled effectively. The carburettor follows the basic principle of atmospheric pressure and as a result, a poor mixture is produced. This leads to an incomplete combustion and hence, higher emission levels that results in various health problems related to air pollution, where it is reported that 13% of the burden of diseases in developing countries and 2% to 6% in developed countries are related to air pollution [5]. To handle this issue, regulating bodies for automotive emissions have come up with emission regulations, which are becoming more and more stringent from time to time [6]. Therefore, fuel injection system (FIS) is expected to be one of the most promising technologies towards improved fuel economy and driving performance as well as reduced engine-out pollutant emissions [7,8].

Fuel injection technology has been around for nearly as long as the automotive industry itself, although crudeness, unreliability and cost made it economically impractical for mainstream automobiles until the 1980s [9,10]. FIS is a system that mixes air with fuel in an internal combustion (IC) engine. It has been used widely in gasoline and diesel engines. Early injection systems used mechanical methods to meter the fuel, known as mechanical fuel injection. In a modern design, FIS consists of mainly electronic components including electronic solenoids, which act as injectors to inject the fuel [11,12]. Basic FIS consists of a fuel pump, a pump regulator, an injector, an electronic control unit (ECU) and various sensors to measure various parameters related to the crank/cam position, flow of air, and exhaust gas oxygen. The operation of the FIS is electronically controlled by the ECU to ensure optimum performance by maintaining the correct amount of A/F produced by the engine so as to avoid problems such as knocking and detonation of the engine.

A retrofit fuel injection technology has been introduced by past researchers to provide the benefits of fuel injection systems to the existing small, carburetted engine motorcycles. The benefits of the retrofit system include its lower implementation cost and simplicity compared to the commercially available fuel injection system. Several studies on the retrofit fuel injection system for small, carburetted motorcycles have been conducted and one of the main challenges in implementing the retrofit system is to adapt it into the existing system [13–15]. Despite this, most retrofit fuel injection systems are able to deliver better performance than the carburettor system.

Since the retrofit FIS can provide a low-cost but effective solution towards better fuel economy and cleaner exhaust emissions for existing small, carburetted motorcycles, it should be given more attention. Therefore, this paper aims to provide a detailed review on the retrofit fuel injection technology developed for small gasoline spark ignition (SI) motorcycle engine from 50 cc to 350 cc as a low-cost alternative to reduce fuel costs and to improve exhaust emissions.

2. Retrofit fuel injection system (FIS) technology on spark ignition (SI) engine

There are several retrofit FIS concepts for use on small capacity carburetted engines developed by past researchers. These have given some enlightenment on how the system should be operated, along with the experimental setup. Usually, the engine's mechanical and electrical systems were modified to include a small automotive style port fuel injector with dedicated throttle body/manifold design, fuel pump, pressure regulator and engine control unit (ECU), together with additional mounted sensors such as temperature sensor, pressure sensor and oxygen sensor at certain parts of the system [16]. In other words, the carburetted motorcycle is retrofitted with the fuel-injection component by replacing the carburettor and manifold parts, while retaining all the conventional components in the motorcycle, i.e. the engine and electrical systems. Most retrofit systems utilize the use of the original spark ignition setting that comes with the engine or factory setting, which is known as the 'stock setting'. This approach has been used to produce simple and low cost working systems so as to avoid major modifications in the original system to meet the requirements of the targeted retrofit technology.

In a modern commercial fuel injection system, the ECU controls the engine status in real-time by controlling the amount of fuel supplied, as well as the angle of the ignition advance [17,18]. The status of the engine is defined by the current rotational speed (in rotations per minute, RPM) and charge, measured as the degree of the throttle opening or the pressure in the suction manifold [19]. The ECU also depends on the indications of the oxygen sensor to measure the oxygen level in the combustion gases. This measurement informs the ECU whether the supply of fuel in the cylinders is too lean (too little fuel) or too rich (too much fuel). Corrections,

based on the measurements of certain sensors, are made to obtain a mixture with a composition as close as possible to the stoichiometric composition. For example, the corrections are the data concerning the thermal condition of the engine, the temperature of the sucked air and the absolute pressure [20–22]. The data concerning the quantity of fuel, as well as the angle of the ignition advance, are most often stored in the form of maps, namely, the fuel map and the ignition map [23–25]. Each of these maps defines a three-dimensional surface over a grid of coordinates, presenting the conditions of the engine, as shown in Fig. 3. The maps assist the ECU in making corrections of the existing fuel data and determine the correct amount of fuel needed by the engine in real-time.

The modern FIS control concept is also used in the retrofit FIS. The main difference is whether the system controls the angle of the ignition advance or not, but most low-cost retrofit FIS do not fully control the spark advance. Usually, the ECU of the retrofit FIS directly reads the stock ignition timing, reads the data from sensors, and then calculates and controls the system by changing the necessary control variable such as the injection timing. However, for the fully applied retrofit FIS, where almost all the electrical systems around the engine are replaced, the system is likely to operate as the commercialized FIS and the cost is also higher.

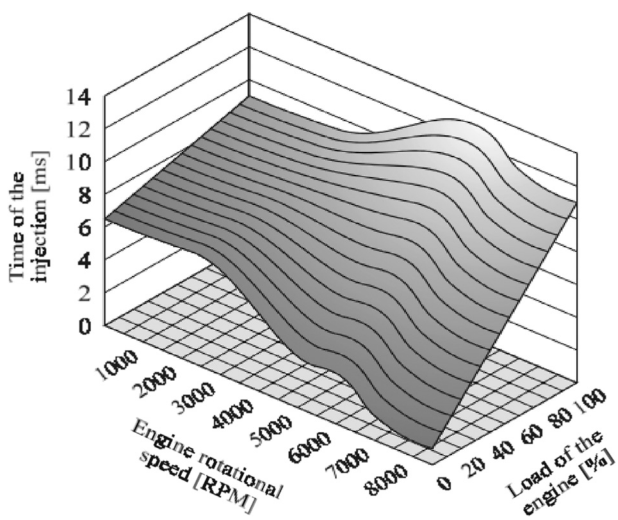

Fig. 3. An example of fuel map.

3. Variant of fuel injection schemes for retrofit FIS

The first step to develop the retrofit FIS is to determine the most appropriate fuel injection scheme to be applied in the system. In this section, three fuel injection schemes for gasoline engines will be discussed. These schemes are defined by their fuel-injection locations, which are the throttle body injection (TBI), the port-fuel injection (PFI) and the direct in-cylinder injection (DI).

3.1. A throttle body injection (TBI) as fuel injection scheme

A TBI system is also known as single-point or central fuel injection system, where electrically controlled fuel injector valves are incorporated into the throttle body [26]. This is almost a bolt-in replacement for the carburettor, so the automakers do not have to make any drastic changes to their engine designs. The mixing of air and fuel takes place behind the throttle plate, which is the same concept applied in the carburettor [27]. In [28], TBI concept has been applied in a 4-stroke, 13.4 kW (18 HP), 350 cc motorcycle engine. The experimental engine test setup was designed to operate in a carburetion mode as well as in an injection mode. This was made possible by fabricating a new throttle body to be added to the existing engine's components. The new throttle body was placed between the original manifold and carburettor in its original position. The injector body was mounted at an angle of 45° to the axis of intake manifold so that the injection of fuel takes place in a direction opposite the intake airflow. This design was made to ensure better mixing of air and fuel before entering the combustion chamber. The injector nozzle was placed at a distance of 01.165 m from the intake port.

To verify the effectiveness of the retrofit system in [28], a comparative study was made between the carburetion mode and the injection mode. From the study, the use of the TBI scheme for the retrofit FIS has improved the engine performance significantly in terms of brake power, fuel consumption and brake torque compared to the carburettor system. The air to fuel ratio has also improved, which means, better ratio is created for optimum combustion and engine performance. In terms of emission performance, there is a substantial reduction in HC and CO gasses, and increase in the CO_2 and NO_x gasses, which indicate better fuel

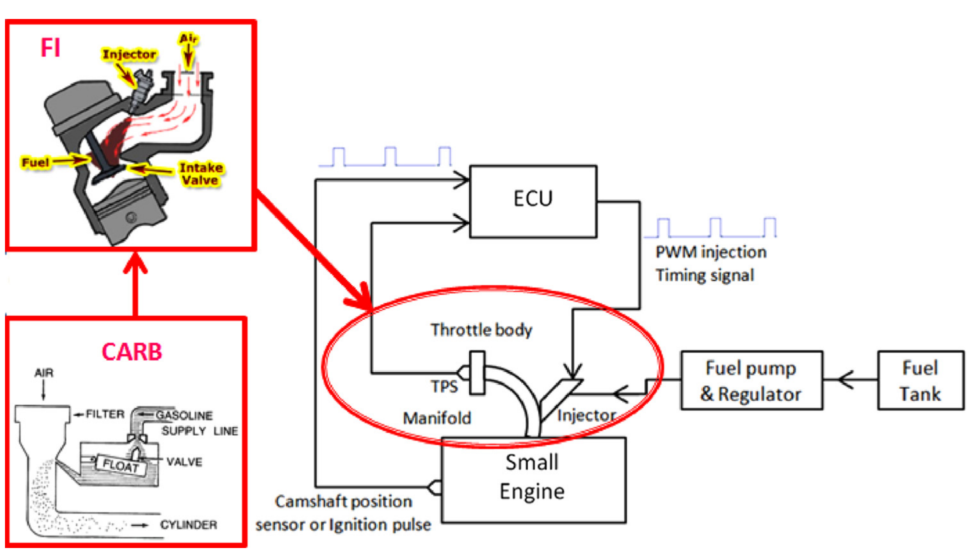

Fig. 4. Retrofit FIS setup of 125 cc engine.

conversion (better combustion and more heat released to produce more power) when compared to the same engine operating in the carburetion mode.

3.2. A port fuel injection (PFI) as fuel injection scheme

In a PFI approach, the low-pressure fuel injector mounted in the intake-port supplies the exact quantity of fuel to mix with air just after the intake valve is opened [29]. This is different from the TBI approach where the mixing of air and fuel takes place behind the throttle plate. The mixture of air and fuel in PFI system will become homogenous in the intake manifold before the intake valve is opened. Then, the mixture is drawn into the combustion chamber just like the working principle of a carburettor. Recently, a retrofit PFI system for a 125 cc engine has been developed in [30–32]. Fig. 4 shows the schematic setup of the system. Based on Fig. 4, the existing carburettor and its intake manifold were replaced with the retrofit PFI kit that consist of throttle body with manifold-mounted injector, fuel pump, ECU and throttle position sensor. In the research conducted in [30,31], an optimum results for engine performance and emissions were obtained with a specific manifold and injector angles, shown in Fig. 5, after considering the configuration of the engine used as well as the available space for the retrofit system.

The study in [30–32] shows no improvement on fuel consumption compared to the carburettor system on the 125 cc test engine but the emission of CO and NO_x is greatly reduced (by more than 50%). No reduction on HC emission was achieved compared to the carburettor system. In [33], the system was controlled by a dedicated ECU developed using the 16-bit high performance; enhanced FLASH microcontrollers PIC 18F452 as the main chip. The ECU collected some data such as the engine speed (in RPM) from the existing charging system of the motorcycle, the throttle position from the throttle position sensor and the camshaft position from the camshaft position sensor. These signals were processed and used in controlling the engine operation. The working principle of the developed ECU is shown in Fig. 6.

In [34,35], a case study on a new carburetted 120 cc engine, which is a common type of small motorcycles in South East Asia, being retrofitted with PFI kit has been conducted. The system is

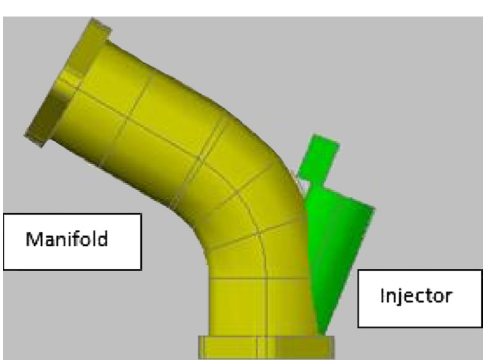

Fig. 5. Configuration design of the intake manifolds and injector.

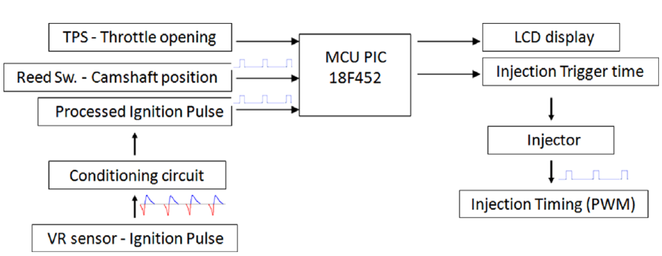

Fig. 6. Working principle of the ECU in retrofit FIS.

operated using a commercial ECU and tested on a dynamometer with stock carburettor settings. The overall system included a small automotive style port fuel injector, a fuel pump, a pressure regulator, a throttle position sensor and a camshaft-mounted speed pickup/index wheel. The throttle position sensor is operated in tandem with the carburettor's slide throttle and the intake manifold was modified to mount the fuel injector at the intake path of the engine. In this study, the performance comparison between the carburettor system and the FI system on the same 120 cc engine was made based on the brake specific fuel consumption and exhaust emissions concentration of HC, CO, CO_2, and NO_x. The retrofit PFI indeed has reduced 11% of the fuel consumption of the 120 cc engine compared to the carburettor system at a cruise speed of 55 km/h. In terms of emission, the HC and CO emissions were reduced by 55% and 96% respectively while the NO_x emission has doubled compared to carburettor system.

There are also certain PFI retrofit systems that require modification of most of the electrical system around a 4-cylinder engine such as superbikes and cars in [36–40]. This type of system was able to change the ignition timing and spark advance relative to engine load and speed. However, this approach is usually applied to a 4-cylinder engine such as to the 1996 Kawasaki ZX-6R motorcycle to produce an optimized performance, as discussed in [36]. The 1996 Kawasaki ZX-6R motorcycle was converted from a four-carburettor intake and non-load sensitive ignition to a programmable electronic fuel injection system for performance enhancement. However, the cost to implement this system was quite high and it required a more complicated system structure and control than that of a single-cylinder engine.

3.3. A direct injection (DI) as fuel injection scheme

Gasoline direct injection (GDI) is a new development in engine technology. It has been claimed that this type of engine can improve fuel efficiency, provide higher power delivery and produce lower emission compared to the traditional gasoline or diesel engine. A DI system admits fuel directly into the combustion chamber, which is totally different from the TBI and PFI approaches in fuel injecting positions [41]. The system can inject fuel just after the exhaust port closes to avoid the fuel leaking out the exhaust port. This greatly reduces pollution caused by the conventional carburetted two-stroke engine, where a large portion of the air/fuel mixture is typically short circuited into the exhaust port during the scavenging process [42]. In recent years, the use of the DI scheme in retrofit FIS among researchers has increased. Even though the cost can be high, the DI technology has shown a great ability to reduce emission and increase the engine's performance while improving fuel economy compared to other fuel injection schemes.

The smallest carburetted engine that has been retrofitted using the DI approach is a 50-cc, 2-stroke engine in [43]. The system is based on the "accumulator" fuel injection operating principle, which involves pressurizing fuel within an injection nozzle and subsequently releasing the pressurized fuel into the combustion chamber on command. This concept provides very short injection duration throughout the dynamic operating range of the engine as well as high injection frequency capability. The addition of full authority electronic control to the direct fuel injection system provides control flexibility and the opportunity for speed and load dependent calibration of the fuel injection event. The combination of unique components, control schemes and combustion systems has resulted in a flexible retrofit DI solution, which is also applicable to low-cost two-stroke engines.

A retrofit DI system in the form of a kit has also been developed to replace the existing carburettor system on the motorcycle engine. For example, a retrofit DI system has been developed for

Kawasaki HDIII in [44,45]; a 125 cc, 2-stroke motorcycle from Philippines that is commonly used as a taxi. The system incorporates the air blast direct injection (ABDI). In the ABDI system, the fuel is injected into a cavity in an air rail, which is separated from the combustion chamber by an outwardly opening, solenoid-actuated poppet valve called the "blast valve". Pressurized air is provided to the air rail by a mechanical pump, which is driven by the crankshaft. When the blast valve is opened, the air "blasts" the fuel into the combustion chamber and finely atomizing it as it enters the combustion chamber.

The study in [44] is further improved in [45] by using the compression pressurize direct injection (CPDI). The CPDI system uses most of the same components as the ABDI system, but now the blast valve is responsible for the blasting of the fuel, as well as re-charging of the mixing cavity, replacing the air rail. Both DI techniques have greatly reduced the emissions of HC (88% for ABDI and 86% for CPDI) compared to the carburetted engine. CO emissions have also been reduced (49% for ABDI and 83% for CPDI), while NO_x emissions have doubled for the ABDI system, and nearly tripled for the CPDI system. The lower CO and higher NO_x emissions of the CPDI system are believed to be due to the CPDI system being operating leaner than the ABDI system. Hence, the CPDI has better fuel economy compared to ABDI and carburettor (40% for CPDI and 32% of ABDI).

4. Comparison between retrofit fuel injection schemes

The TBI scheme has a major drawback compared to the PFI. The use of TBI created a fuel-pooling problem in the intake manifold [46]. Here, the injector sprays an amount of fuel that strikes the intake manifold walls and condensation takes place, forming a fuel film on the manifold wall. This means a fraction of the fuel injected directly enters the cylinder. Evaporation of this puddle also causes fuel from previous injections to enter the cylinder after some time delay. Usually, ECU will likely to add a delay routine to compensate for this problem and adjust the corrected fuel to be injected into the engine [47]. To minimize this error, PFI is mostly chosen as a fuel-injection scheme because it has faster acceleration rate by atomizing the fuel directly to the inlet valve port. With this advantage, there will be less fuel sticking on the manifold wall. Hence, fuel film created on the manifold wall is reduced and so, more accurate amount of fuel flows into the cylinder for better air to fuel ratio (A/F) control. Furthermore, to eliminate the fuel transport delay or fuel pooling effect, DI scheme is used. In modern FIS, DI has proven to have an optimum performance above TBI and PFI. However, TBI and PFI systems are usually more preferred than the DI system if a low-cost and simpler control solution for a retrofit FIS is of main concern. This is because the DI system is more complicated, requires higher implementation cost and more sophisticated control of the fuel injection, air-fuel mixing and combustion processes compared to the PFI system [48,49].

Recently, the use of DI scheme for retrofit system has also been applied to 110 cc and 118 cc engines, which are 2-stroke motorcycle engines typical to the South Asian market [50–52]. However, these studies focus on the use of gaseous fuel such as compressed natural gas (CNG) or liquid petroleum gas (LPG), which is not covered in this paper. Both gasses fuel may cost less than the equivalent amount of gasoline. A gaseous fuel DI system may also cost less than an air-assisted gasoline DI system as the gaseous system does not require a fuel pump, air pump or liquid fuel injector. Based on the economic analysis in [51], Table 1 shows the estimated retrofit cost and the major components required by a gasoline electronic fuel injection (EFI) system, a gasoline DI system and a gaseous DI system for a typical small motorcycle. It can be seen that the DI system requires more components than the TBI and the PFI system; hence the cost is higher.

Table 1
Major component of various fuel injection configurations and estimated retrofit costs.

Parts used		FI scheme (gasoline)		FI scheme (gaseous)
		TBI/PFI	DI	DI
Fuel pump		Yes	Yes	
Regulator		Yes	Yes	Yes
Air pump			Yes	
ECU		Yes	Yes	Yes
Injectors	Gasoline	Yes	Yes	
	Air/gas		Yes	Yes
Sensors	TPS	Yes	Yes	Yes
	Crank pickup	Yes	Yes	Yes
	MAP	Yes	Yes	Yes
	Temperature	Yes	Yes	Yes
	Pressure tank			Yes
Estimated cost (USD)		125	250	150

5. Conclusions

In this paper, a review of the retrofit fuel injection technology applied on the existing carburetted 50 cc to 350 cc motorcycle gasoline engine has been discussed. The retrofit FIS technology can serve as a low-cost alternative in an effort to improve fuel economy and exhaust emissions by retrofitting the fuel injection components into existing engines to replace the carburettors. Three fuel injection schemes (TBI, PFI and DI) have been highlighted based on their usage, advantages and limitations as the potential retrofit systems. The TBI and the PFI schemes result in simpler and lower cost systems. To minimize the error caused by the fuel transport delay or pooling effect, PFI scheme is preferred but, to eliminate the pooling effect and for a better fuel injection control, the DI is more effective. Even though the retrofit PFI system has shown a satisfactory result, its performance is overwhelmed by the retrofit DI system. The better-controlled DI system results in better performance, better fuel economy and cleaner exhaust emissions compared to the PFI system. However, the cost of the retrofit DI system is much higher than that of the PFI system.

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